Energy Storage Testing and Analysis
High Power and High Energy Development

This presentation does not contain any proprietary or confidential information

Project ID: es_09_murphy

Tim Murphy, Jeff Belt, Kevin Gering, Jon Christophersen and Sergiy Sazhin

Energy Storage and Transportation Systems

DOE/EERE Vehicle Technologies Program, Annual Merit Review

May 19, 2009

Overview

Timeline

On-going Activity
Began in 1985

Budget

FY 2008: $2M
FY 2009: $2M

Barriers

Testing and analysis strategies are critical to accurately characterizing the **performance, life, reliability and cost** of advanced energy storage devices for vehicles.

Partners

Argonne National Laboratory

- Procedures, Analysis, Applied Research, Life Prediction Tools

Sandia National Laboratories

- Abuse Tolerance, Life Validation Methods

National Renewable Energy Laboratory

- Thermal Imaging, Analysis, Models

USABC- Energy Storage Technical Team

Various Universities and Industry

- Life Prediction Testing, State-of-Health and Models

Objectives

- **Support Vehicle Technologies Program, Energy Storage Technology Development:**
  - Develop and validate the testing and analysis procedures used to track progress of program deliverables against DOE goals and objectives (technical targets).
  - Validation and diagnostic testing of United States Advanced Battery Consortium (USABC) deliverables in scheduled phases of the development projects (Batteries and Ultracapacitors).
  - Benchmark testing of non-USABC prototype devices of interest on a case by case basis.
  - Support the development of life prediction models for technologies of interest (Also part of the ABRT presentations).
  - Maintain a flexible state-of-the-art energy storage test facility at the INL capable of supporting current and future development activities.
  - Closely coordinate these activities with other national laboratories to maximize the value to development projects.
  - Help identify technologies capable of meeting technical targets

Milestones

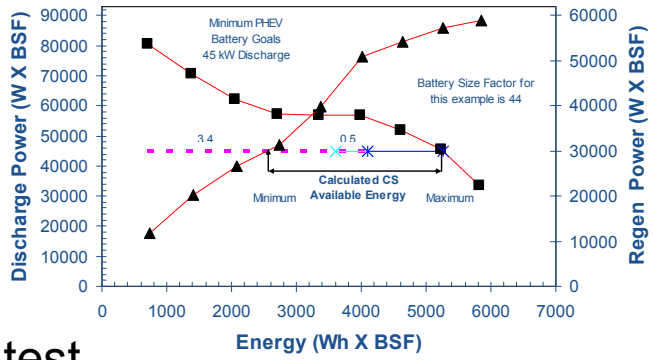
- **Manuals for Testing, Analysis, and Life Predictions focused on supporting technology development aimed at meeting the DOE/United States Advanced Battery Consortium (USABC) Technical Targets for batteries.**
  - Plug-in HEV procedures manual (rev. 0) published 2008
    - Revision expected 2010
  - Battery Life Estimation (BLE) manual (w/ANL), Sept. 2009
  - TLVT procedures manual (INEEL-EXT-04-01986) revision after BLE completed and new round of validation tests conducted 2010.
- **Testing of Program Energy Storage Device Deliverables**
  - Annual testing status report on all testing projects to DOE in November.
  - Quarterly testing status reports to USABC Tech Team.
- **Diagnostic Testing and Applied Research activities**
  - Reported under Applied Battery Research for Transportation Program
  - Related poster presentations esp_03_gering, and esp_05_gering

Approach

①	②	③	④
Testing	**Analysis**	**Modeling**	**R&D (ABRT)**
USABC and Other program deliverables •Batteries •Ultracapacitors Cells, Modules, and Full Size Systems Testing protocol is driven by customer needs (USABC and DOE).	Standards developed for data acquisition, analysis, quality, and management. Data accuracy and uncertainty analysis. Huge amounts of data are generated. Software analysis tools have been developed.	Key modeling tools: • Arrhenius Analysis • Equivalent Circuit Models • Life Prediction Models • TLVT protocol • Chemical Physics Models • Kinetics Models	Applied research explores basic issues of battery performance and aging. • Specialized diagnostic tests and measurements • Interfacial Regions (SEI, DL) • Coin Cell Testing • Molecular-scale modeling

Accomplishments/Progress/Results

- Developed and issued draft Plug-In Hybrid Electric Vehicle (PHEV) battery test procedures
  - Ref: "U.S. Department of Energy FreedomCAR & Vehicle Technologies Program, FreedomCAR Battery Test Manual For Plug-In Hybrid Electric Vehicles"
    - Validation and review ongoing in FY09
    - First official version was published March FY08
      - INL/EXT-07-12536
    - Revision expected in FY10
      - USABC Work Group for procedures reviewing



- Ongoing support to program participants for other test manuals:
  - FreedomCAR Battery Test Manual For Power-Assist HEV's
    - DOE/ID-11069
  - FreedomCAR Ultracapacitor Test Manual
    - DOE/NE-ID-11173

Accomplishments/Progress/Results

- **Testing of USABC Deliverables In FY2008/2009**

  – Johnson Controls – Saft, HEV Power Assist, Lithium-Ion
    - Long-Term combined calendar/cycle life testing on FY2001 technology
      – 24 cell study, ongoing, quarterly and annual reports delivered
    - VL7P cell technology for calendar and cycle life testing, FY2006/07 technology
      – 32 cells, design process improvements for cost reduction, calendar life and low temperature performance.
      – Completed, reports delivered
    - VL7P cell technology for cycle life testing, FY2008 technology
      – 3 cells, design process improvements for cost reduction, calendar life and low temperature performance.
      – Ongoing, quarterly and annual reports delivered

Accomplishments/Progress/Results

- **Testing of USABC Deliverables In FY2009**
  - Johnson Controls Saft, HEV Battery, Lithium-Ion
    - VL7P battery pack technology for cycle life testing
    - 344 V to 210 V, 6.8 Ah system
    - Recent start, March 2009

Accomplishments/Progress/Results

- **Testing of USABC Deliverables In FY2008/2009**

  – Enerdel, HEV Power Assist, Lithium-Ion
  - Calendar life study of new novel chemistry, FY2007 technology
    – 10 cells, Enerdel low cost electrode materials, complete
    – Reports delivered
  - Calendar and cycle life testing of Argonne National Lab (ANL) anode technology delivered to Enerdel for cell construction and optimization.
    – 20 cells, complete, ANL developed low cost anode material
    – 4 modules, starting in July 09
    – FY 2007 technology, quarterly and annual reports
  - PHEV Calendar and cycle life testing of Argonne National Lab (ANL) improved anode technology delivered to Enerdel for cell construction and optimization.
    – 20 cells, starting in Apr 09, ANL developed low cost anode material

Accomplishments/Progress/Results

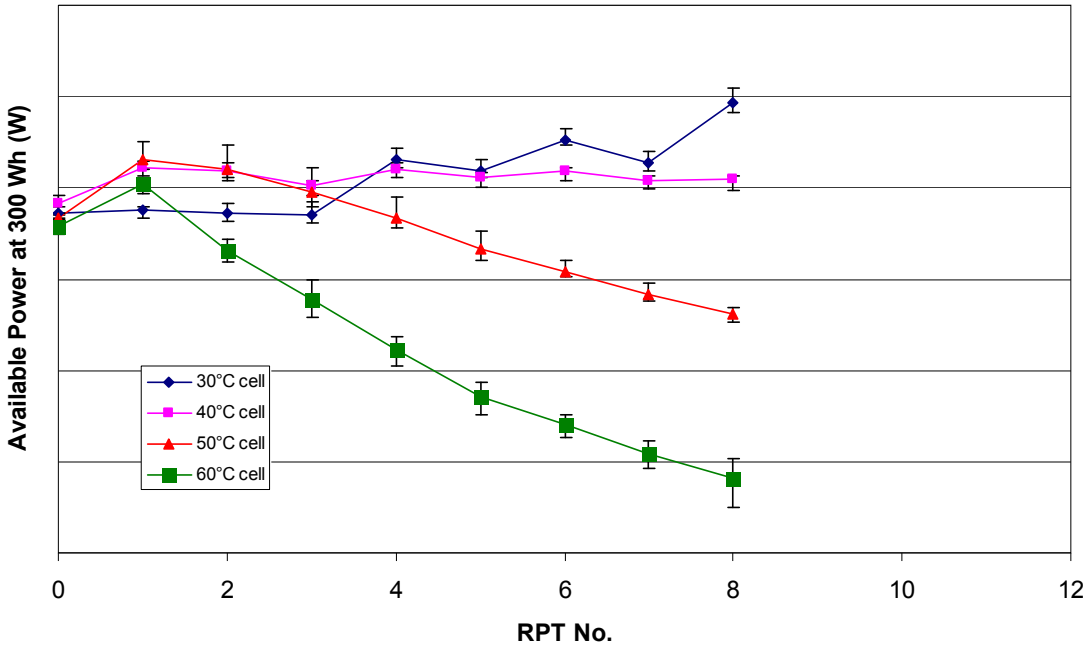
- **Testing of USABC Deliverables In FY2008/2009**

  – Compact Power, HEV Power Assist, Lithium-Ion

  - Calendar life focused testing on FY2007 technology from large battery manufacturer, unique approach
    – 12 cells, complete, reports delivered
  - Calendar and Cycle life focused testing on FY2008 technology from large battery manufacturer, unique approach
    – 20 cells, ongoing, quarterly and annual reports delivered
  - PHEV cycle and calendar life focused testing on FY2008 technology from large battery manufacturer, unique approach
    – 40 cells, ongoing, quarterly and annual reports delivered

Accomplishments/Progress/Results

- **Example Test Results From Li-Ion Battery Using the Accelerated Protocols - Available Power vs Time/Temp.**
  - Calendar life test consisted of 1 pulse per day at the 5C rate
  - Data covers about 8 months of testing
  - Available Power results are from the L-HPPC test
  - The calendar life at 30°C shows no degradation
  - The initial increase in power is generally attributed to a secondary mechanism that tapers off early on in testing.
  - Increased temperature results in increased power fade.

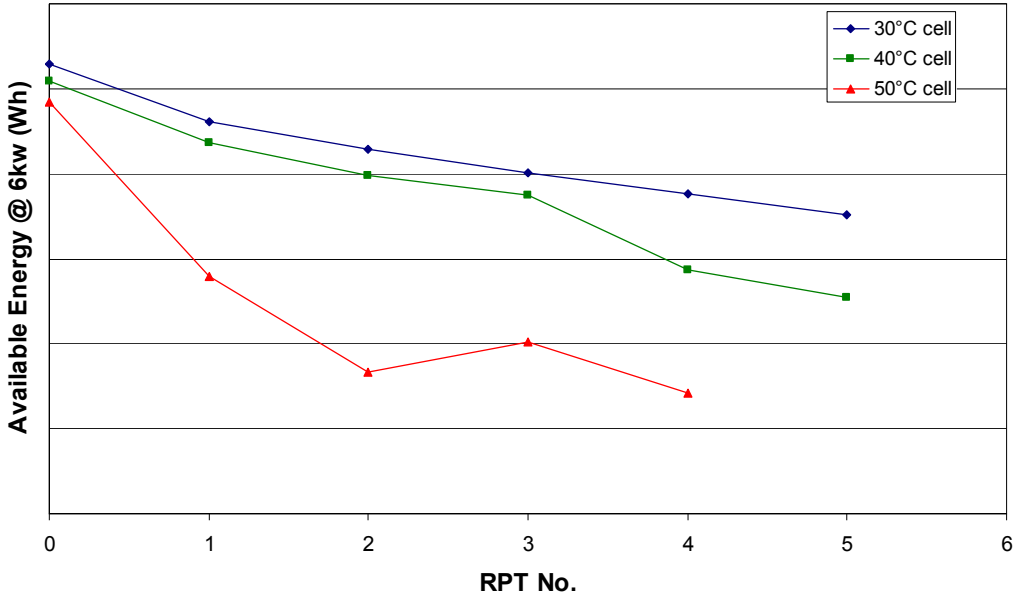


Accomplishments/Progress/Results

- **Testing of USABC Deliverables In FY2008/2009**
  - Ultracapacitors, Carbon based double layer capacitors
    - JSR Micro, FY2008/09 technology
      - 3 cells to be delivered in April 2009
    - NessCAP, FY2006/07 technology
      - Cycle and calendar life testing, energy density improvements
      - 8 cells and 2 modules in study aimed at improving energy and studying effects of temperature on performance.
      - Complete, reports delivered

Accomplishments/Progress/Results

- **Example Test Results From High-Energy Ultracapacitor Using the Accelerated Protocols - Available Energy vs Time/Temp.**
  - Cycle life test was performed with the UC10 profile, 75k cycles per RPT
  - Available Energy results are from the L-HPPC test
  - Capacitors have completed 375 k cycles
  - The cycle life at all temperatures show high cell variability
  - Increased temperature results in increased energy fade.



Accomplishments/Progress/Results

- **Benchmark Testing of Non-USABC Deliverables**

  – NLE (Japan) Power Assist, Lithium-Ion
    - Novel materials for cycle life and calendar life testing
    - 2, 48 volt modules
    - Cycle life testing completed, report delivered
    - Calendar life testing ongoing, quarterly and annual reports delivered

  – Sanyo (Japan) Minimum PHEV, Lithium-Ion
    - PHEV Manual validation testing, ongoing
    - 85, 18650 size cells
    - Calendar and cycle life testing start 2009, quarterly and annual reports will be delivered

Accomplishments/Progress/Results

- **Benchmark Testing of Non-USABC Deliverables**

  – Altairnano Power Assist (HEV), Lithium-Ion
    - Novel materials for cycle life and calendar life testing
    - 20, 3.5 Ah cells
    - Calendar and cycle life testing started, quarterly and annual reports will be delivered

  – Altairnano Minimum PHEV, Lithium-Ion
    - Novel materials for cycle life testing
    - 20, 11 Ah cells
    - Charge Depleting cycle life testing started, quarterly and annual reports will be delivered

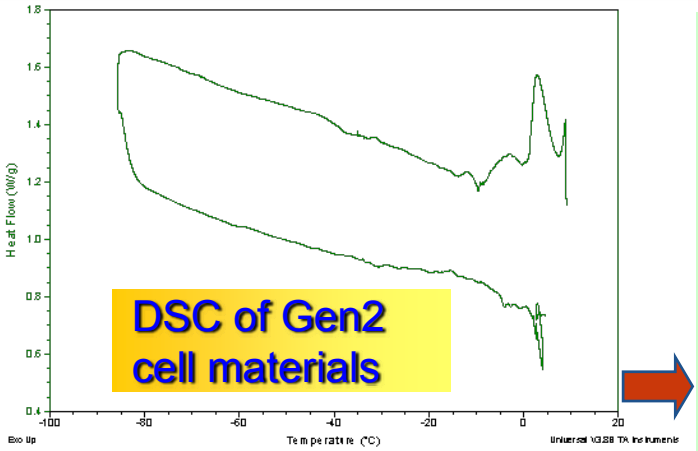
Accomplishments/Progress/Results

- **Benchmark Testing of Non-USABC Deliverables**
  - Advanced Lead-Acid Battery Technology (Micro-hybrid applications)
    - Collaboration with Pb-Acid Battery Consortium (ALABC) to study performance improvements from doped carbon electrodes.
    - Deliverables expected for testing 2009/2010
    - Ultrabattery
      - Unique battery-carbon capacitor electrode configuration
      - 2, 12 volt modules
      - Life testing ongoing, quarterly and annual reports delivered
    - Firefly (ANL)
  - Limited industry data suggests improvements in power/energy and cycle life
  - Limited performance and life testing at INL and ANL

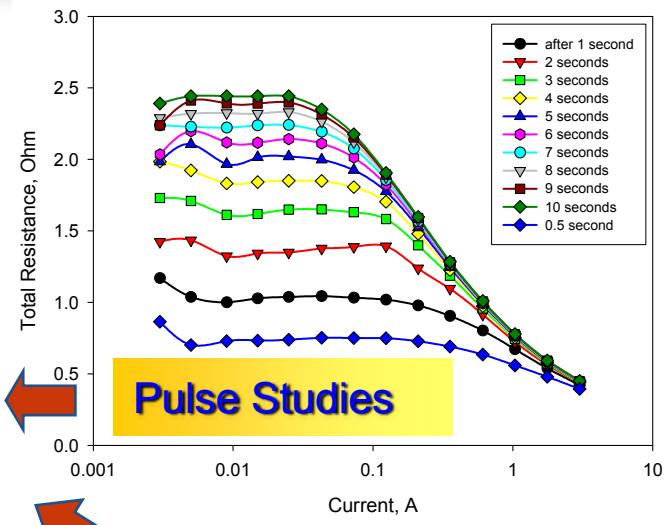
Accomplishments/Progress/Results

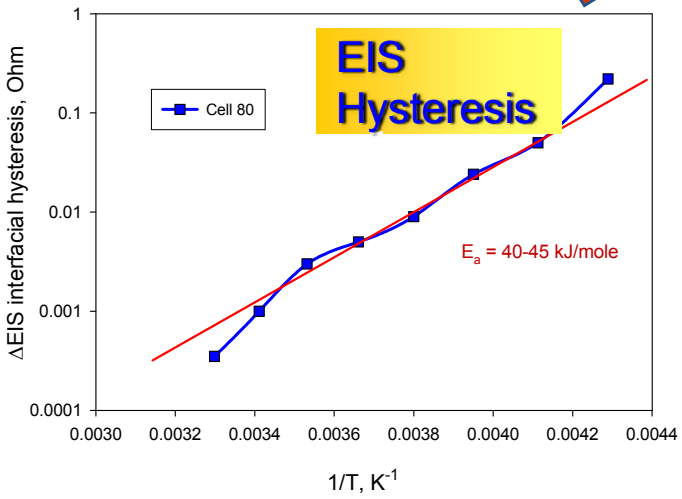
- **INL Focus on Diagnostic Testing (DT)**
  - Tools used to determine fundamental mechanisms that govern performance of Li-ion cells.
  - Highly focused, well-designed experiments or test conditions that target specific issues toward mechanistic-level knowledge of device performance, and,
  - A self-consistent theoretical and mathematical framework that enables intelligent data analysis and modeling.
  - DT can be designed to gain knowledge regarding the effect of
    - chemistry on performance
    - interfacial behavior
    - aging mechanisms
    - thermodynamic processes
    - kinetic limitations etc.

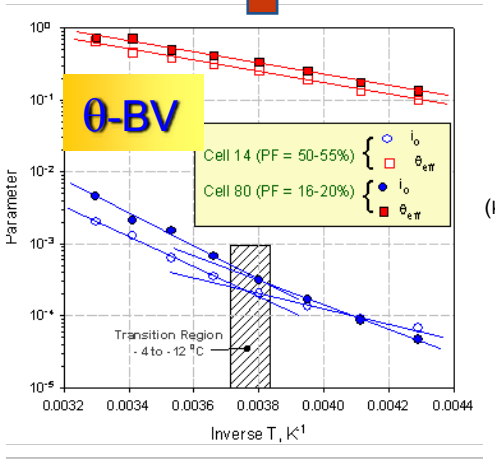
Accomplishments/Progress/Results

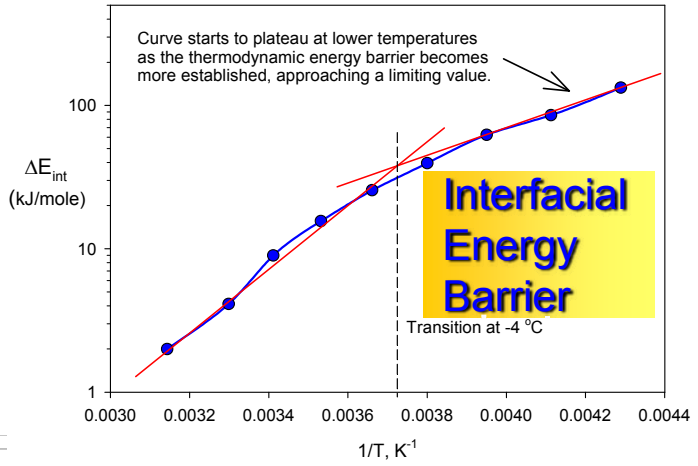


These results infer one or more *thermodynamic processes* occur to increase interfacial impedance at lower temperatures (e.g., increased solvent ordering, rearrangement, adsorption, or phase formation at electrode interfaces and inside porous regions).









Accomplishments/Progress/Results

- **Diagnostic Testing**
  - Gen3 Enerland Pouch Cells: Cycle-life testing of cells at 45°C complete; cells at 25°C remain on test through mid-April 2009.
  - Diagnostic Testing and Modeling of Gen2 18650 cells provided powerful insights into true kinetic limitations at low temperatures.
  - Robust equivalent circuit models have been developed and validated over the temperature regime, using Gen2 data (coin cell & 18650).
  - Advanced Electrolyte Model has been used to support electrochemical cell modeling, predict properties of new electrolytes, and has been further adapted to perform transport calculations for critical interfacial regions (DL).
  - Statistical model for Gen3 Enerland formation process can now predict cell capacity and resistance for off-matrix conditions and can predict conditions for time-minimized formation protocol.
  - Currently, a large suite of Diagnostic Testing is underway for Sanyo 18650 Li-ion cells.
  - Diagnostic testing and modeling point to thermodynamic mechanisms effecting performance.

Accomplishments/Progress/Results

- **Technology Life Verification Testing (TLVT) FY2008/2009**
  - Collaboration with ANL,SNL,LBNL
  - Accelerated testing and modeling for life prediction
  - Battery Life Estimator Manual
    - New Battery Life Estimator Manual nearly complete
    - Will be published in FY09
  - Supported the development of life estimation software tool
    - ANL lead
  - Validation testing
    - TLVT validation testing is expected to begin in May 2009
    - Supported by focused diagnostic tests
  - Life prediction modeling activities ongoing

Accomplishments/Progress/Results

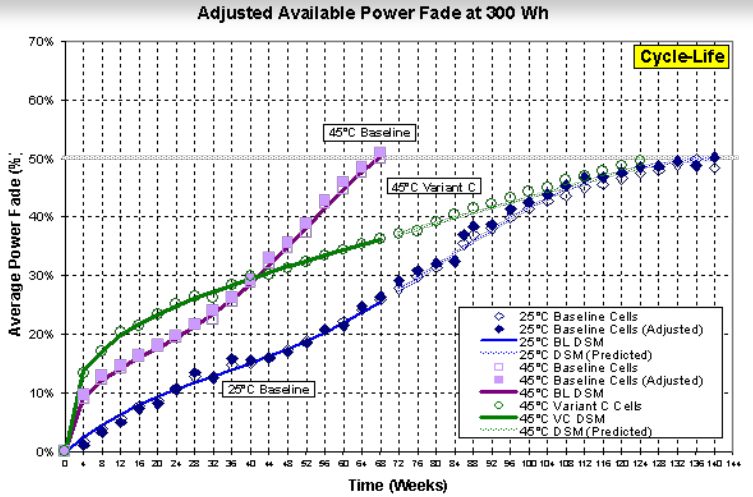
- **Smart Battery Status Monitor**
  - Method/hardware to quickly and accurately predict the remaining life of energy storage devices (battery or capacitor).
    - Rapid in-situ impedance measurement techniques
    - Determine impedance at multiple frequencies accurately
      - Two promising methods are under development and have been verified under no-load conditions using available lithium ion cells at INL.
    - Collaborative effort between INL, Montana Tech, and Qualtech Systems, Inc.
    - Three new invention disclosures have been submitted for real-time estimation of battery impedance.
    - Upgraded hardware/software impedance monitoring device is scheduled to begin validation testing in May 2009.
      - Transition to on-board impedance monitoring with standard HPPC/EIS measurements using available cells.

Activities for Next Fiscal Year

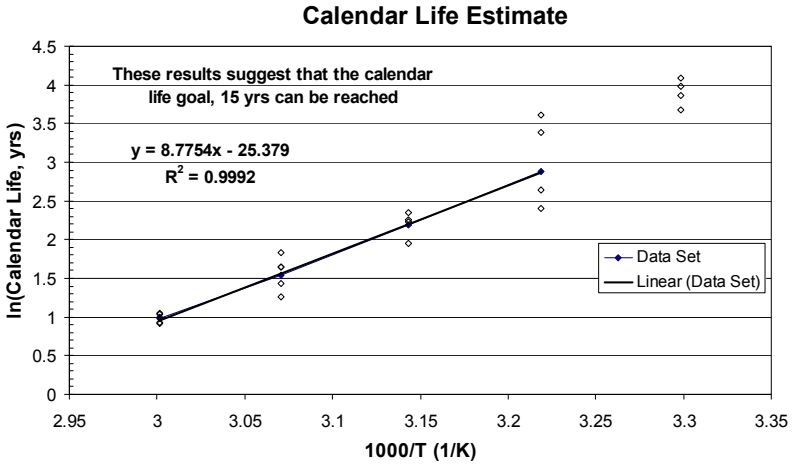
- Develop and validate the testing and analysis procedures used to status program deliverables against DOE goals and objectives (technical targets).
  - Continue to refine, modify, or add testing and analysis procedures to the PHEV Test Manual as user comments and issues are resolved. A Manual revision is expected in the FY10 timeframe.
  - Develop BLE and revised TLVT Manuals
  - Continue to support the HEV Power Assist and Ultracapacitor Test Procedures Manuals.
- Validation testing of USABC deliverables in scheduled phases of the development projects.
  - Cycle Life testing of JCS 340V Battery Pack
  - Project deliverables expected from Compact Power and Enerdel. Cells first and eventually prototype vehicle packs are planned.
  - Provide test procedure and analysis support to A123 and Johnson Controls – Saft PHEV projects at ANL.
  - Performance and life testing on deliverables under the HEV Power Assist projects from Johnson Controls – Saft, Compact Power, and Enerdel.
  - Complete testing of Ultracapacitors from the NessCAP project.

Activities for Next Fiscal Year

- Continue to conduct benchmark type testing of non-USABC prototype devices of interest on a case by case basis.
  - Novel chemistries and designs
  - Ultracapacitors
- Continue to support the development of life prediction models for technologies of interest.
  - As empirical models become more robust and true physical models emerge, accelerated testing becomes more accurate and efficient.
    - Arrhenius Methods
    - TLVT methodology
    - Predictive Kinetics approaches (DSM)
    - Others



Average power fade vs. time for DOE-ATD Li-ion cells for test data (symbols) and predictions made by the DSM model (curves). The "adjusted" notation refers to data adjusted to true test temperature.



Activities for Next Fiscal Year

Diagnostic Testing Activities

- Support high-voltage electrolyte development and modeling for high energy Li-ion PHEV cells
- Support performance and life modeling of high energy Li-ion PHEV cells.
- Support cycle-life and calendar-life evaluation of high energy Li-ion PHEV cells.

- Key aspects of cell performance will be targeted by Diagnostic Testing, with the aim to determine mechanistic-level information regarding both optimal and limited performance.

- **Primary Targets**
  - **Interfacial Phenomena as Surmised through Molecular Processes**
  - **Kinetic Limitations as a f(T, SOC, current, aging, chemistry)**
  - **Contributions by Competing Thermodynamic Processes**
  - **Aging Mechanisms of Capacity Fade and Impedance Rise (and Path Dependence thereof)**
  - **New Electrolyte Solvents as Additives for Abuse Tolerance**
  - **Effects of thermal cycling on aging**

Activities for next fiscal year

- Technology Life Verification Testing/Manual Validation (TLVT)
  - Continue validation testing and methods development.
    - Supplemental testing to include various cell chemistries to evaluate the effects of path dependence, thermal cycling, cold cranking, others to determine effects on the life estimation.
    - Study affects on life estimations from high energy PHEV profiles.
    - Revise TLVT Manual.
- Battery Life Estimation (BLE) Manual
  - Support ANL in development of standardized battery life estimation methods. Beta testing of ANL software tools and models.
- Smart Battery Status Monitor (SBSM)
  - Continue efforts to develop and verify real time impedance measuring techniques on various cell chemistries.
  - Verify that methods are effective at predicting state-of-health real time during extended life cycling conditions.
  - Testing and analysis will follow TLVT testing schedules.

Summary

- Advanced batteries that meet or exceed DOE Vehicle Technologies Program goals and objectives will have a significant effect on vehicle fuel use nationally.
  - Testing is critical to the success of this effort.
- The broad testing activity is under constant review and is improved or modified annually as needs change.
  - Targets, Procedures, Analysis Tools, Models etc.
  - USABC Deliverables, Benchmark Testing of promising technologies
  - Diagnostic Testing and applied research to identify key performance issues
  - Uncertainty and accuracy measurements are used.
  - Close coordination with National Labs and suppliers.
- Technology Transfer occurs due to direct collaboration between DOE, suppliers, automobile industry, and the test facilities.
- FY09/10 – continue to improve, expand, and advance testing/analysis and diagnostic testing capabilities.